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Galle S, Malcolm P, Derave W, De Clercq D. 2014. Enhancing performance during inclined loaded walking with a powered ankle-foot exoskeleton. Eur J Appl Physiol 114: 2341-2351.

ABSTRACT

PURPOSE. A simple ankle-foot exoskeleton that assists plantarflexion during push-off can reduce the metabolic power during walking. This suggests that walking performance during a maximal incremental exercise could be improved with an exoskeleton if the exoskeleton is still efficient during maximal exercise intensities. Therefore, we quantified the walking performance during a maximal incremental exercise test with a powered and unpowered exoskeleton: uphill walking with progressively higher weights.

METHODS. Nine female subjects performed two incremental exercise tests with an exoskeleton: one day with (powered condition) and another day without (unpowered condition) plantarflexion assistance. Subjects walked on an inclined treadmill (15%) at 5 $km \cdot h^{-1}$ and 5% of body weight was added every 3 min until exhaustion.

RESULTS. At volitional termination no significant differences were found between the powered and unpowered condition for blood lactate concentration (respectively 7.93±2.49; 8.14±2.24$mmol \cdot L^{-1}$), heart rate (respectively 190.00±6.50; 191.78±6.50bpm), Borg score (respectively 18.57±0.79; 18.93±0.73) and $\dot{V}O_2$ peak (respectively 40.55±2.78; 40.55±3.05$ml \cdot min^{-1} \cdot kg^{-1}$). Thus, subjects were able to reach the same (near) maximal effort in both conditions. However, subjects continued the exercise test longer in the powered condition and carried 7.07±3.34kg more weight because of the assistance of the exoskeleton.

CONCLUSIONS. Our results show that plantarflexion assistance during push-off can increase walking performance during a maximal exercise test as subjects were able to carry more weight. This emphasizes the importance of acting on the ankle joint in assistive devices and the potential of simple ankle-foot exoskeletons for reducing metabolic power and increasing weight carrying capability, even during maximal intensities.

INTRODUCTION

Exoskeletons that assist the lower limbs during locomotion have improved much in the last decade and experts in the field believe that they will soon have an important role in daily life (Ferris 2007). While most research is focused on technical enhancements, a quantitative evaluation of the effectiveness is often missing (Dollar and Herr 2008). The metabolic energy expenditure, often calculated as metabolic power ($W \cdot kg^{-1}$) based on oxygen consumption and carbon dioxide using a standard equation (Brockway 1987) and body weight normalization, is a key value in the evaluation of several exoskeleton devices (Galle et al. 2013a; Malcolm et al. 2013; Mooney et al. 2014; Norris et al. 2007a; Sawicki and Ferris 2008, 2009a, 2009b; Wehner et al. 2013). Regardless of the functional goal of the device, reducing the metabolic power will improve the usability of the exoskeleton (Ferris et al. 2007) and can therefore be considered a prime outcome when evaluating exoskeleton effectiveness, that can even be used to drive kinematic behavior with exoskeletons (Collins and Jackson 2013).

During walking, half of the positive joint work is done by the ankle during push-off (Winter 1983). Therefore, much potential is attributed to powered exoskeletons that assist ankle plantarflexion. Walking with powered exoskeletons with pneumatic muscles that assist plantarflexion during push-off results in reductions in metabolic power of 10 to 17% compared to walking with an unpowered exoskeleton (without plantarflexion assistance)(Galle et al. 2013a; Malcolm et al. 2013; Norris et al. 2007a; Sawicki and Ferris 2008, 2009a, 2009b). Despite the increased weight of the device, Malcolm et al. (2013) were the first to report a 6% reduction in metabolic power for powered exoskeleton walking compared to walking with normal shoes if the actuation timing of the exoskeleton was optimal. While they showed that it was possible to reduce metabolic power below the level of normal walking, their device was not autonomous, meaning that it needed power and air supply and extensive hardware which was not carried by the user. However, Mooney et al. (2014) showed that it is possible to make a fully autonomous exoskeleton that assists plantarflexion and that can reduce the metabolic power of loaded walking with 8% versus normal walking if the design of the device is altered in order to reduce distal mass. Furthermore, there is increasing progress in energy recycling approaches (Collins and Kuo 2010; Donelan et al. 2008; Li et al. 2009; Malcolm et al. 2013, Unal et al. 2012) and soft exosuits (Wehner 2013), which makes it likely that autonomous ankle-foot exoskeletons can become a permanent fixture in daily life.

Exoskeletons can be used as assistive devices for patients, *e.g.* to restore normal gait (Blaya and Herr 2004; Sawicki et al. 2006) but the applications for healthy subjects are less obvious. Because ankle-foot exoskeletons can reduce the metabolic power during walking, it should be possible to walk with higher external workloads (due to increasing slope, speed or carrying weights) when assisted by an exoskeleton, while the metabolic power requirements remain constant. At higher workloads it can be expected that ankle-foot exoskeletons have the potential to increase walking performance during a maximal incremental exercise test if two conditions are met: (A) the powered exoskeleton must still be effective in terms of reducing metabolic power during maximal exercise intensities and (B) it must be feasible for the user to walk with the exoskeleton with minimal encumbrance during maximal exercise intensities. If both these conditions are fulfilled, one could expect an external workload (slope, speed or carried weight) during walking with a powered exoskeleton that transcends the maximal achievable workload during walking without an exoskeleton.

However, we are not aware of any succesfull attempts in increasing walking performance during maximal exercise intensities as current research is mainly focused on submaximal intensities (Galle et al. 2013a; Malcolm et al. 2013; Mooney et al. 2014; Norris et al. 2007a; Sawicki and Ferris 2008, 2009a, 2009b). Studying higher intensities is also useful for applications in specific populations (*e.g.* prolonged or loaded walking for soldiers and rescue workers) and will give more insight into human-exoskeleton interaction, *e.g.* on the efficiency and the consistency of the assistance over increasing intensities. Higher intensities would also contribute to taking exoskeletons out of their 'normal' environment and allow to use them as a tool to resolve fundamental questions in biomechanics, motor control and physiology, as suggested by Ferris et al. (2007). In example, the influence of muscle fatigue on overall fatigue could be studied by assisting or resisting specific muscles (Malcolm 2009) with an exoskeleton during exercise until exhaustion.

The pneumatic artificial muscles that are mostly used in ankle-foot exoskeletons have numerous benefits for assisted walking like the low weight to force ratio and their compliant behavior (Daerden and Lefeber 2000). Although they need compressed air supply, which makes them less useful for daily life applications, they are frequently used in a lab environment to study general principles on human-exoskeleton interaction. Because they cannot achieve the high inflation and deflation frequency needed for running, higher intensities without drastically changing the walking pattern (Franz and Kram 2012; Harman et al. 2000; Lay et al. 2006; Lay et al. 2007) can only be achieved during uphill walking and by adding external weights (Kramer 2010). It seems reasonable that subjects can benefit from push-off assistance during loaded uphill walking as previous research showed that subjects can benefit from an exoskeleton during uphill walking (Sawicki and Ferris 2009a) and during load carrying (Mooney et al. 2014). Therefore, exoskeleton locomotion during maximal exercise intensities could be tested with the weighted walking test (Klimek and Klimek 2007) or a similar alternative. The weighted walking test is a method to assess aerobic power during walking: subjects walk on a treadmill with an inclination of 12% at a speed of 1.8 $m \cdot s^{-1}$ and every 3 min 5% of body weight is added until exhaustion. Klimek and Klimek (2007) showed that this is a valid alternative for a maximal cycling or running exercise test.

The aim of our study is to quantify the walking performance during a maximal incremental exercise with a simple powered ankle-foot exoskeleton with plantarflexion assistance (Galle et al. 2013a; Malcolm et al. 2013). Therefore, an incremental walking exercise test similar to the weighted walking test (Klimek and Klimek 2007) will be used and the walking performance during this test will be expressed as the weight that subjects are carrying at volitional termination of the test. We choose to focus on the comparison of powered versus unpowered walking because our main research question concerns the influence of push-off assistance during higher intensities. Our first hypothesis (A) is that the assistance of the powered exoskeleton can still reduce metabolic power when compared with an unpowered exoskeleton during walking with high external workloads, induced by a slope and carrying additional weights. As the steering algorithm of the exoskeleton and the air pressure of the pneumatic muscles remain unaltered during the exercise test, we assume that the assistance pattern of the exoskeleton will be similar over increasing weights and will therefore result in an absolute reduction in metabolic power that is similar during the subsequent intervals of the exercise test. Our second hypothesis (B) is that it is possible to reach maximal metabolic effort both with a powered and an unpowered ankle-foot exoskeleton. As a result of these two hypotheses an increase in maximal carried weight and thus walking performance is expected in the powered condition.

METHODS

Subjects

Nine healthy female subjects [age 21.3 yr (SD 2.2), weight 69.8 kg (SD 9.2), height 171.4 cm (SD 4.6)] participated in the study. Female subjects of normal height and weight were chosen because they fit best in the exoskeleton and because exoskeleton assistance would have a greater effect on their relatively low body weight. They had no previous experience with walking with exoskeletons but all had experience with treadmill walking. All participants gave written informed consent and the protocol was approved by the ethical committee of the Ghent University Hospital.

Exoskeleton

The exoskeleton is a device that can be worn by healthy subjects and that fits around the left and right lower leg (Fig. 1A). It consists of an ankle-foot orthosis with a hinge at the ankle joint and a McKibben pneumatic muscle attached at the dorsal side. The exoskeleton has a weight of 0.76 kg at each foot and fits in sport shoes where footswitches (Multimec 5E/5G, Mec, Ballerup, Denmark) are built in. These footswitches allow to detect foot contact, which is used to impose a specific timing and duration in which the pneumatic muscles are inflated. The pneumatic muscles are connected to air supply and when inflated (air pressure, ± 3.5 Bar) they shorten and cause ankle plantarflexion (Fig. 1B). The goal of our exoskeleton is to add plantarflexion power to the ankle during push-off (Galle et al. 2013a, 2013b; Malcolm et al. 2013). The pneumatic muscles can be turned on and turned off at specific time intervals based on footswitch signals and are triggered with a computer program (Labview, National Instruments, Austin, TX). Start of pneumatic muscle actuation was set at 43 % of stride for level walking (Malcolm et al. 2013) and at 36 % of stride for uphill walking (Galle et al. 2013b) as previous studies showed that these actuation timings are metabolically optimal. Pneumatic muscles were turned off after 63 % of stride, coinciding with toe-off in all conditions. Peak pressure of the pneumatic muscles and peak mechanical power of the exoskeleton occurs in between start and end of pneumatic muscle actuation (Galle et al. 2013a, 2013b; Malcolm et al. 2013).

Protocol

All participants performed two incremental exercise tests, similar to the weighted walking test (Klimek and Klimek 2007) on two different days with one week in between. These tests were performed under two randomized exoskeleton conditions: on one day with actuation of the pneumatic muscles to assist plantarflexion during push-off (powered condition) and on another day without pneumatic muscle actuation (unpowered condition). Before the exercise test subjects performed a standing rest trial of 4 min to determine resting energy expenditure and a 22 min habituation session (Galle et al. 2013a) on a level treadmill (HP Cosmos, Nussdorf-Traunstein, Germany) at 5 $km \cdot h^{-1}$ to learn to walk with the exoskeleton. In the powered condition both the habituation and the exercise test were done with a powered exoskeleton and in the unpowered condition both the habituation and the exercise test were done with an unpowered exoskeleton. The exercise test was performed at 5 $km \cdot h^{-1}$ on a treadmill with a 15 % slope. Subjects walked during 3 min intervals with 1 min of rest in between. In the first interval subjects walked on the treadmill with an unloaded weight vest (no weight) and every 3 min a weight corresponding to 5 % of body weight was added to the weight vest (Fig. 1). Once all compartments were filled (20 kg), a backpack was used to add more weights. In between 3 min intervals, 1 min of rest allowed us to add weights and collect blood lactate samples. Subjects were instructed to continue the walking protocol until voluntarily termination due to exhaustion.

Data Collection

During the entire protocol subjects wore a heart rate belt, a nose-clip and breathed in a mouthpiece. Heart rate (RS 400, Polar, Oulu, Finland), O_2 consumption and CO_2 production (Oxycon Pro, Jaeger GMBH, Höchberg, Germany) were measured during the entire protocol. In the first 30 sec after every 3 min interval 65 µL capillary blood samples were collected from the tip of the middle or third finger of the left hand and analyzed within the next 35 sec with a blood gas analyzer (Radiometer, ABL-90 Flex, Brønshøj, Denmark). At termination of the exercise test subjects were asked to score perceived exertion on the Borg scale (Borg 1973). In 2 subjects this failed due to human errors, resulting in reliable values for 7 subjects. An end-test blood lactate sample was taken 2 min after exercise termination due to weight unloading immediately after exercise termination as subjects were carrying weights of over 20 kg.

Data analysis

End-test blood lactate concentration was the blood lactate concentration at exercise termination and peak heart rate was the highest measured heart rate value, always in the last min of the exercise test. Metabolic energy expenditure was estimated with the formula of Brockway (Brockway 1987) based on 30 sec mean values of O_2 consumption and CO_2 production and divided by subjects body weight to calculate metabolic power ($W \cdot kg^{-1}$). Metabolic power of the second and third min of the 4 min standing rest trial in the beginning of the experiment was subtracted from gross metabolic power to calculate net metabolic power.

Net metabolic power for all 3 min intervals was calculated based on the last min of each interval. Peak net metabolic power was the metabolic power in the last min of the last completed walking interval. In 2 out of 151 measures, metabolic power was deleted from the analysis as the net metabolic power of the interval was more than 10% lower compared to the previous interval, which is unlikely and the result of measurement errors (*e.g.* due to nose clip displacement). $\dot{V}O_2$ peak was determined based on the highest 30 sec mean value of the entire protocol, always in the last min of the exercise test. Maximal carried weight was the weight that subjects were carrying in the last completed 3 min interval. Total weight was defined as the total weight that subjects were moving against gravity, which is the sum of body weight, exoskeleton weight, shoe weight and the additional weight that subjects carried.

As the number of completed intervals varied between subjects, linear regressions were used to model the individual relationship between net metabolic power and the carried weight for each 3 min interval for both the powered and unpowered exercise test. All individual regressions were based on at least 6 data points. The individual y-intercepts and slopes of the regressions could then be averaged to compute the mean linear regression for the powered and the unpowered exercise test. The carried weight in the regression analysis was expressed as a percentage of the maximal weight that subjects carried in the unpowered exercise test, which was referred to as the maximal unpowered weight. Thereby, all subjects terminated the unpowered exercise test with a weight of 100 % of maximal unpowered weight.

Because the number of completed 3 min intervals varied between subjects, it was not possible to calculate population averages for every interval for blood lactate. Therefore, blood lactate concentration was calculated for 3 instants during the unpowered exercise tests: for the first (= without weight), the middle (= 50 % maximal unpowered weight) and the last interval of the exercise test (= maximal unpowered weight). This resulted in 3 lactate values (for the beginning, the middle and the end of the unpowered exercise test) that could be averaged across subjects. These were compared with the lactate averages for the intervals of the powered exercise test with the same carried weight. For an even number of intervals the mean of the two middle intervals was used for the middle value.

A similar approach was used to see if a steady state in the net metabolic power was reached in the last minute of every 3 min interval by comparing the 6 subsequent 30 sec averages of net metabolic power. As the number of completed 3 min intervals varied between subjects, population averages could not be calculated for every interval. Therefore this analysis was done for all subjects for the first (= without weight), the middle (= 50 % maximal unpowered weight) and the last interval of the unpowered exercise test (= maximal unpowered weight). For an even number of intervals the mean of the two middle intervals was used for the middle value. This resulted in net metabolic power for 3 intervals (for the beginning, the middle and the end of the unpowered exercise test) that could be averaged across subjects. These were compared with the intervals of the powered exercise test with the same carried weight.

Exoskeleton mechanical power

During the powered condition, the exoskeleton delivers additional mechanical power to the ankle joint (Galle et al. 2013a; Malcolm et al. 2013). Exoskeleton mechanical power was not measured during the exercise tests but in order to evaluate the magnitude of the exoskeleton assistance, 2 representative subjects out of the 9 subjects performed an additional protocol on a different day. During this protocol, exoskeleton mechanical power was measured for the right leg during uphill walking with progressively higher weight carrying. Subjects walked on an inclined treadmill (15%) at 5 $km \cdot h^{-1}$ during 1 min intervals with 2 min rest in between. The weight in the different intervals was identical to the weight that these subjects carried in the powered exercise test (0 to 31 kg over 11 intervals) in order to get a reliable estimation for the amount of additional power delivered by the exoskeleton during the consecutive intervals of the previous exercise test. Reflective markers (4) on the shank and foot allowed us to detect foot contact and ankle joint angle with MaxTraq software (Innovasion Systems, Columbiaville, MI, USA) on high speed video recordings (100 Hz, Redlake, Morgan Hill, CA, USA). A load cell (100 Hz, 210 Series, Richmond Industries Ltd., Reading, UK) was connected to the right pneumatic muscle to measure the pneumatic muscle force during walking and was recorded in synchronization with the high speed video during 10 sec, which equals approximately 10 strides of uphill walking. Moment arm of the pneumatic muscle was measured as the perpendicular distance between the exoskeleton joint and the pneumatic muscle for the right leg (=0.08 m). Ankle angle and load cell data were filtered with a 2^{nd} order Butterworth low-pass filter (cut-off frequency 12 Hz). Load cell data were used to calculate pneumatic muscle force and were multiplied with pneumatic muscle moment arm to calculate pneumatic muscle torque of the right leg. Mechanical power of the exoskeleton for the right leg was then calculated by multiplying ankle angular velocity (= first derivative of ankle joint angle) and pneumatic muscle torque and divided by body weight. Exoskeleton power per stride was then averaged to calculate net exoskeleton mechanical power per stride and was averaged for 8 to 9 consecutive strides as previous studies showed rather large variations between steps (Malcolm et al. 2013; Sawicki and Ferris 2008, 2009a).

Statistics

Cohens' d statistics (Cohen 1977) were used to calculate effect sizes for our main outcomes which are the y-intercepts of the linear regressions, indicating a difference in metabolic power between powered and unpowered walking with the same carried weight, and the carried weight in the last interval of the powered and unpowered exercise test, indicating the walking performance in the powered and unpowered exercise test. Effect sizes were higher then 1, indicating large effect sizes.

Regression analysis and other statistics were done with SPSS Statistics 20 (IBM, Armonk, NY). Paired samples t-tests with the α level of significance set at $P \leq 0.05$ were done: to compare end-test physiological parameters and maximal carried weight between the powered and unpowered exercise test; to search for differences in y-intercepts and slopes of the linear regressions of the powered and unpowered exercise test; to compare blood lactate concentration between powered and unpowered walking. Repeated measures ANOVA with post hoc comparisons and Bonferroni correction and with the α level of significance set at $P \leq 0.05$ were done to check for steady state in the 6 subsequent 30 sec averages of net metabolic power of the 3 min intervals in the beginning, the middle and the end of the exercise test.

RESULTS

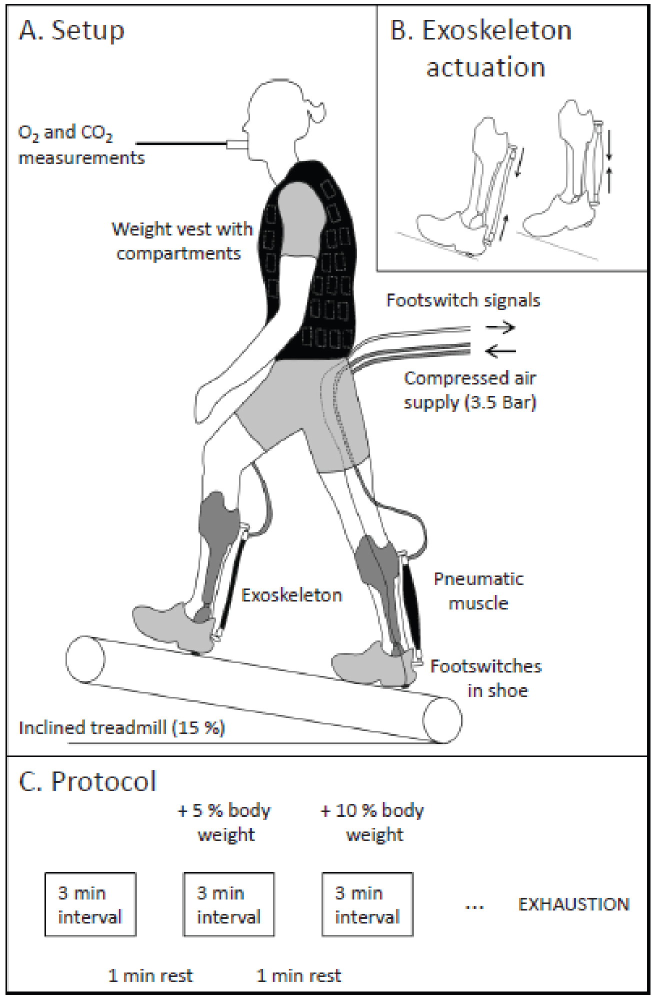

Fig. 1. Experimental setup (A), Exoskeleton actuation (B) and Experimental protocol (C).

(A) Experimental setup: subjects wore an exoskeleton and vest with several compartments that could be filled with weights. During the entire experiment O_2 and CO_2 measurements were recorded with a mouthpiece. In the powered condition footswitches in the heel detected foot contact and the pneumatic muscles of the exoskeleton were turned on during push off by means of compressed air inflation.

(B) Exoskeleton actuation: in the powered condition the inflated air in the pneumatic muscles caused a shortening of the pneumatic muscles and thereby induced plantarflexion assistance during the push-off.

(C) Protocol: subjects performed a powered and unpowered maximal walking exercise test with progressively higher weight carrying on an inclined treadmill (15%) at 5 km·h^{-1}. Every 3 min 5% of body weight was added until subjects terminated the exercise test due to exhaustion. In between the intervals 1 min of rest allowed to add weights and collect blood samples and perception data.

All subjects sustained the powered and unpowered exercise test for at least 6 intervals, thereby carrying more than 30% of body weight during uphill walking when terminating the exercise tests. The end-test physiological parameters that were collected at volitional termination of the exercise test were similar in the powered and unpowered condition: blood lactate concentration, heart rate, Borg scale score, peak net metabolic power and $\dot{V}O_2$ peak did not differ at the end of both exercise tests (Table 1).

Table 1. *End-test physiological and performance measures for the unpowered and powered exercise test*

	Condition				*P*
	Unpowered exercise test		Powered exercise test		
End-test blood lactate ($mmol \cdot L^{-1}$)	8.14	(2.24)	7.93	(2.49)	0.811
Peak heart rate (bpm)	191.78	(6.50)	190.00	(6.50)	0.558
End-test Borg scale (6-20 scale)	18.93	(0.73)	18.57	(0.79)	0.182
Peak net metabolic power ($W \cdot kg^{-1}$)	12.52	(0.91)	12.48	(1.02)	0.915
$\dot{V}O_2$ peak ($ml \cdot min^{-1} \cdot kg^{-1}$)	40.55	(3.05)	40.55	(2.78)	0.999
Max. carried weight (kg)	22.47	(3.57)	29.54	(4.13)	≤ 0.001*

End-test values for the unpowered and powered exercise test. See Methods for calculations. Values are means of subjects (SD) and *P* values are the result of paired samples t-tests to search for differences between the powered and unpowered exercise test. * indicate a significant difference between the unpowered and powered exercise test.

Subjects performed better in the powered exercise test than in the unpowered exercise test (Table 1): subjects were able to sustain the walking protocol longer and thereby carried a 7.07 ± 3.34 kg higher weight at the end of the exercise test in the powered condition. In terms of the total weight that subjects were moving against gravity (which is the sum of body weight, exoskeleton weight, shoe weight and the weight that subjects carried), subjects were able to transport 7.7 ± 4.1 % more total weight against gravity in the powered condition than in the unpowered condition.

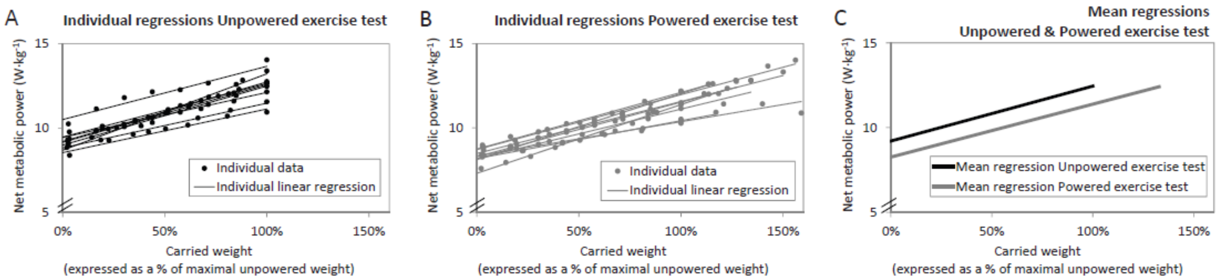

Fig. 2. Linear regression between net metabolic power and carried weight for the exercise tests. All individual data points (●) and individual regressions (thin lines) are plotted for the unpowered (A) and the powered exercise test (B). Based on the individual regressions an average linear regression (thick lines) was calculated for both the powered and unpowered exercise test (C), see Methods and Table 2 for details. Carried weight was expressed as a % of maximal unpowered weight during both exercise tests. In this way the exercise test is terminated with a weight that corresponds to 100% of the maximal unpowered weight for all subjects in the unpowered exercise test.

In the first interval of the exercise test, when subjects were walking uphill without carrying weights, net metabolic power was 8.0 ± 6.2 % lower for powered exoskeleton walking (8.48 ± 0.42 $W \cdot kg^{-1}$) than for unpowered exoskeleton walking (9.24 ± 0.53 $W \cdot kg^{-1}$). At the end of the exercise test, when carrying a weight corresponding to 100% of the maximal unpowered weight (22.5 ± 3.6kg) net metabolic power was 10.1 ± 6.8 % lower for powered exoskeleton walking (10.85 ± 0.67 $W \cdot kg^{-1}$) compared to unpowered exoskeleton walking (12.52 ± 0.91 $W \cdot kg^{-1}$). A linear regression was done for every individual for net metabolic power versus carried weight, expressed as a % of the maximal unpowered weight (Fig. 2). All individuals showed a significant linear regression between net metabolic power and carried weight for both the powered and unpowered exercise test (Table 2). The y-intercepts of these linear regressions were significantly lower (-0.95 ± 0.72 $W \cdot kg^{-1}$) for the powered exercise tests than for the unpowered exercise tests, indicating lower net metabolic power for walking without weights in the powered condition. No significant difference between the powered and unpowered exercise test could be found for the slopes of the linear regression, indicating a constant difference in net metabolic power. In other words, a parallel linear relationship was found between the powered and unpowered exercise test with a constant significantly lower net metabolic power over the entire protocol in the powered condition.

The exoskeleton mechanical power measurements that were collected in a subsample on an additional test day showed only small variations over increasing weights (0 to 31 kg). Net exoskeleton mechanical power per stride for the right leg was 0.13 ± 0.01 $W \cdot kg^{-1}$ and 0.12 ± 0.01 $W \cdot kg^{-1}$ for the different intervals with increasing weight for respectively the first and second subject.

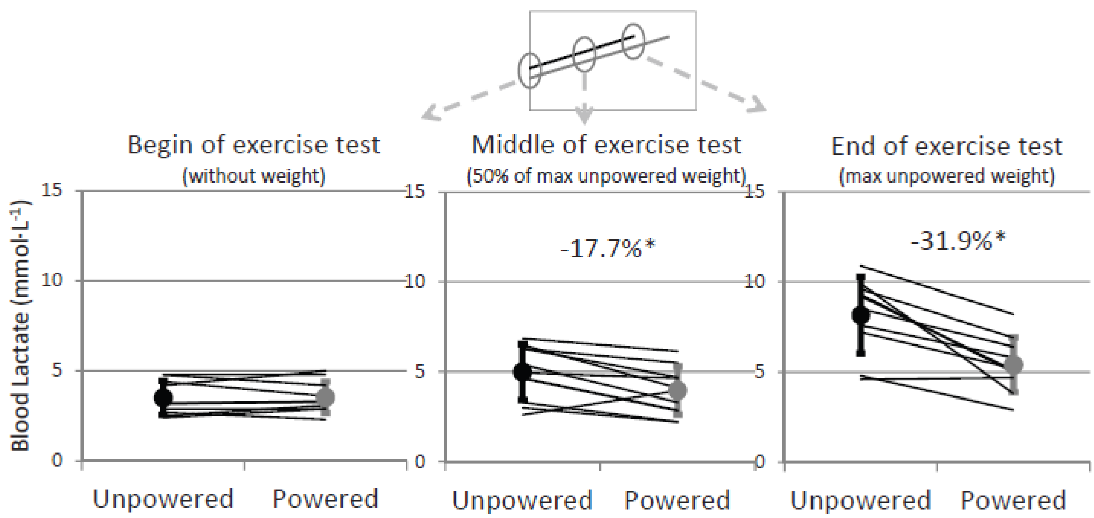

Fig. 3. Blood lactate concentrations for different weight conditions. Mean (●) and individual (thin lines) capillary blood lactate concentrations ($mmol \cdot L^{-1}$) are compared between the powered and unpowered exercise test in the beginning (walking without weights), the middle (with carrying 50% of the maximal unpowered weight =11.5 ± 1.7 kg) and at the end of the exercise tests (with carrying 100% of the maximal unpowered weight =22.5 ± 3.6 kg). Error bars are ± 1 SD of the mean. * indicate significant difference between the powered and unpowered exercise test with paired samples t-test ($P \leq 0.05$). Percentages express the difference in capillary blood lactate concentration between the unpowered and powered exercise test.

In the first interval of the exercise test, when subjects were not carrying weights, blood lactate concentration was not significantly different between the powered (3.54 ± 0.87 mmol·L^{-1}) and unpowered (3.51 ± 0.95 mmol·L^{-1}) condition when walking without weights. During increasing intensities, blood lactate concentration was significantly lower in the powered condition (3.96 ± 1.34 mmol·L^{-1}; 5.40 ± 1.52 mmol·L^{-1}) compared with the unpowered condition (4.99 ± 1.56 mmol·L^{-1}; 8.16 ± 2.12 mmol·L^{-1}) in the middle and at the end of the exercise test, when walking with a weight corresponding to respectively 50 % (11.5 ± 1.7 kg) and 100 % (22.5 ± 3.6 kg) of the maximal unpowered weight (Fig. 3).

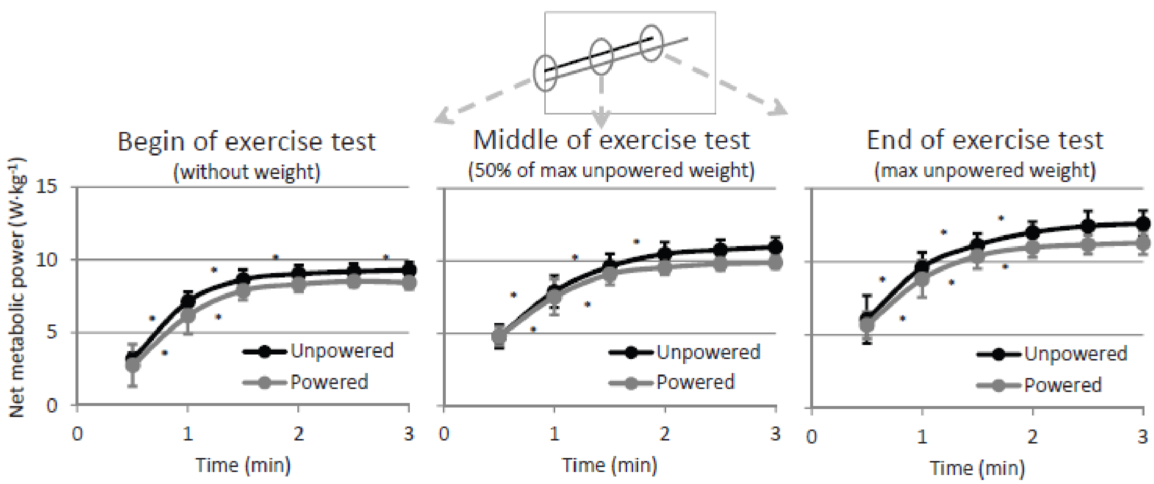

Fig. 4. Changes in net metabolic power during 3 min intervals. The subsequent 30 sec averages for net metabolic power during a 3 min interval are averaged across subjects in the beginning (walking without weights), the middle (with carrying 50% of the maximal unpowered weight =11.5 ± 1.7 kg) and the end of the exercise tests (with carrying 100% of the maximal unpowered weight =22.5 ± 3.6 kg). * indicate significant differences between consecutive 30 sec averages in net metabolic power with Repeated measures ANOVA with post hoc comparisons and Bonferroni correction (*P* ≤ 0.05).

Analysis of the net metabolic power for consecutive 30 sec averages within a 3 min interval in the beginning, the middle and at the end of the exercise test indicated a steady state in net metabolic power after 2 min as no significant differences were found between consecutive 30 sec averages after 2 min (Fig. 4). In the first unpowered condition a significant difference was found between min 2.5 and min 3 but the difference of 0.12±0.08 $W \cdot kg^{-1}$ seems negligible.

DISCUSSION

The aim of our study was to quantify walking performance with a simple powered exoskeleton during a maximal exercise test. During the exercise test, assistance of the exoskeleton resulted in a reduction in net metabolic power of 8 % at lower intensities (walking without weights) and 10% at higher intensities (walking with 100% of maximal unpowered weight). This percentage reduction in net metabolic power is similar with previous research during assisted loaded walking (Mooney et al., 2014) or uphill walking without weights (Sawicki and Ferris 2009a) and emphasizes that subjects can benefit from plantarflexion assistance during uphill loaded walking. Also the lactate values that did not differ between both conditions in the beginning of the exercise test and that differed when intensities increased indicate that the lactate threshold is exceeded later in the exercise test in the powered condition and shows that plantarflexion assistance reduces the effort for a specific workload. These findings are consistent with the regression analysis that showed a parallel linear relationship for powered and unpowered walking when net metabolic power was plotted against carried weight, with a constant reduction of 0.95 ± 0.72 $W \cdot kg^{-1}$ in the powered condition. This confirms our first hypothesis (A): powered ankle-foot exoskeletons can reduce the metabolic power when compared with unpowered walking, also during maximal exercise intensities.

At volitional termination of the exercise tests, end-test physiological measures ($\dot{V}O_2$ peak, peak net metabolic power, peak heart rate, blood lactate concentration and Borg score) were similar for the powered and unpowered condition. While these end-test measures are a little lower than expected for a maximal exercise test, they are corresponding to the reported values for the weighted walking test (Klimek and Klimek 2007) and situated within the boundaries of reported maxima for exercise testing (Herdy and Uhlendorf 2011; Koch et al. 2009; Midgley et al. 2007). Therefore, given the specific characteristics of this uphill walking task, subjects reached maximal oxidative metabolism and at least a near maximal effort. As the effort at volitional termination of the powered and unpowered exercise test can be considered similar and (near) maximal, this confirms our second hypothesis (B) that it is possible to reach maximal metabolic effort both with a powered and an unpowered ankle-foot exoskeleton.

The 3 min intervals that were used in our exercise test might be too short to reach a true steady state in net metabolic power, given the possible slow component in $\dot{V}O_2$ at higher intensities (Zoladz and Korzeniewski 2001). However, analysis of the subsequent 30 sec averages indicate a steady state in the last minute of the interval and intervals with the same duration were also used in a similar exercise test (Klimek and Klimek 2007). As it was not our aim to measure a true $\dot{V}O_2Max$ but to compare the powered and unpowered condition, it seems unlikely that longer intervals would have altered our main conclusions.

Because of the constant reduction in net metabolic power when walking with a powered exoskeleton and because subjects reached the same (near) maximal effort, subjects were able to increase their walking performance by carrying 7.07 ± 3.34 kg more additional weight. When body weight, exoskeleton weight, shoe weight and additional carried weight are taken into account, 8% more total weight was transported against gravity during uphill walking with a powered exoskeleton. Although a training effect might influence our results in the subjects that performed the unpowered exercise test first, all subjects showed an increase in walking performance in the powered condition. We are not aware of any other scientific reports on successful increases in performance during locomotion with the use of exoskeletons. The ratio of the increase in walking performance corresponds to the reduction in metabolic power of 8 to 10% for powered walking versus unpowered walking with the same weight. This emphasizes the direct relationship between the reduction in metabolic power with a powered exoskeleton and the resulting increase in weight carrying performance.

Exoskeleton mechanical power measurements in a subsample of 2 subjects indicate that net exoskeleton mechanical power per stride did not change over increasing weights, which seems in agreement with the constant reduction in net metabolic power based on the regression analysis. Although we did not measure exoskeleton mechanical power during the exercise test, the values of ~0.12 and ~0.13 $W \cdot kg^{-1}$ per leg that were collected on a separate day are in line with the results of other studies on exoskeleton walking (Malcolm et al. 2013; Mooney et al. 2014; Sawicki and Ferris 2008, 2009a, 2009b). The muscular efficieny of positive joint power during steep uphill locomotion is assumed to be ~0.25 (Margaria 1976), which means that the addition of 1 W in positive mechanical exoskeleton power can be expected to cause a reduction in metabolic power of 4 W. It is therefore not surprising that ~0.25 $W \cdot kg^{-1}$ (for both legs) of exoskeleton mechanical power results in a constant reduction of 0.95 ± 0.72 $W \cdot kg^{-1}$ in net metabolic power. Estimations based on the literature (Lay et al. 2007; McIntosh et al. 2006) indicate that the amount of net exoskeleton power that was added to the ankle joint during the powered exercise test represents around 20 % of normal net ankle joint power during uphill walking.

Much attention is paid to loaded walking in a military context as this can determine mission success (Knapik et al. 2012). Developing an exoskeleton that allows to carry more load, increase endurance or reduce metabolic power seems not straightforward (Zoss et al. 2006). Of the few carefully controlled scientific reports of exoskeletons that are intended to increase performance or allow to perform tasks with lower metabolic power, most of them point in the direction of an increase in metabolic power or a decrease in performance when walking with these devices (Gregorczyk et al. 2006, 2010, 2012; Kazerooni and Steger 2006; Pratt 2004; Schiffman et al. 2010; Walsh et al. 2007). Current commercial exoskeletons intended for load bearing are based on structures that transfer the load via rigid beams towards the ground, which reduces the stress on the human musculoskeletal system but increases the mass of the device. Mooney et al. (2014) showed that it is possible to reduce metabolic power of walking with weights with an exoskeleton that has no such load transferring structure but solely relies on assistive power that acts distally at the ankle. While this has the potential disadvantage that increasing the load also increases the stress on the human musculoskeletal system, it reduces the mass of the device. Our results indicate that plantarflexion assistance can increases the weight that subjects can transport with 7.07 ± 3.34 kg and that walking endurance can be increased as subjects continued the exercise test longer. This suggests that also more simple approaches can be useful to assist loaded walking.

In general, our results emphasize the potential of acting on the ankle joint in assistive devices which could be applied in clinical rehabilitation exoskeletons as the ankle-foot complex is often not incorporated (Duerinck et al. 2012), in healthy people to increase performance in terms of endurance and strength and in experimental studies to answer fundamental questions. As subjects were able to use the assistance of the exoskeleton even when fatigued and when carrying heavy loads, future exoskeleton studies can be done in more challenging experimental settings.

The major limitation towards an implementation of our exoskeleton in daily life applications is that it is not autonomous but Mooney et al. (2014) showed that with an altered design, plantarflexion assisting exoskeletons can be made autonomous . However, we see a role for biomechanists and physiologists in studying the human-exoskeleton interaction without being concerned about technical or practical limitations. While this allows to study more fundamental topics (Sawicki and Ferris 2008, 2009a, 2009b), specific knowledge that results from these studies, e.g. on optimal actuation timing (Malcolm et al. 2013), can also be used in the development of autonomous exoskeletons (Mooney et al. 2014). Our choice to compare powered and unpowered walking can also be seen from this perspective as it allows to specifically study the effect of the power assistance to the ankle isolated from the possible side effects of wearing the passive structure of the exoskeleton. Towards practical relevance, the comparison with a standard shoe condition, which is missing in our study, would allow to study the increase in metabolic power because of the movement restrictions and the supplementary weight of the exoskeleton.

We are aware of the smaller reductions in net metabolic power compared to the results with a similar exoskeleton during level walking (Malcolm et al. 2013) and also previous results of uphill walking with our exoskeleton revealed bigger reductions in net metabolic power (Galle et al., 2013b). In order to allow the pneumatic muscles to function continuously during more than 30 min, additional air filters were added to the hardware to prevent dust and water vapor to enter the pneumatic muscles. Post-experiment analysis showed that this modified both the magnitude and the timing of the assistive power. As a previous study showed that actuation timing is an important determinant of the reduction in metabolic power (Malcolm et al., 2013), timing changes may have reduced the effectiveness of the exoskeleton during the exercise test.

In conclusion, we studied walking performance of a powered ankle-foot exoskeleton, which seems relevant for military, recreational and experimental purposes, during a maximal uphill walking exercise test with increasing weights up to 30kg. Assistance of a powered exoskeleton reduced the metabolic power of walking by more than 8% for each weight and allowed subjects to continue the exercise test longer, thereby carrying 7.07±3.34 kg more weight. Although our exoskeleton is not autonomous and a comparison with walking with standard shoes is missing, the results advance exoskeletal research and development into a new level: increasing walking performance during maximal exercise by increasing maximal carried weight during an exercise test with progressively higher weight carrying. We demonstrated that it is possible to reach (near) maximal effort during exoskeleton walking and that plantarflexion assistance is still effective during higher intensities. Our results emphasize the potential of simple ankle-foot exoskeletons and the importance of acting on the ankle joint in assistive devices, even during more challenging tasks .

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